

The Crab Nebula at 850 μm

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Abstract. Observations of the Crab Nebula at 850 μm made with the *Submillimetre Common-User Bolometer Array* (SCUBA) on the James Clerk Maxwell Telescope are presented. A variety of chop-throws and scanning directions was used in these observations, to well sample structure over a range of scales and directions. The resulting image, which was restored using a MEM algorithm, has a resolution of 17 arcsec, and has been compared with a 20-cm VLA image of the Crab Nebula to study spectral index variations. The 850- μm and 20-cm images are very similar, implying that there is little variation in spectral index across the face of the remnant between these wavelengths.

1. Introduction

The Crab Nebula (=G184.6–5.8), the remnant of the SN of AD 1054, shows a centrally brightened morphology, and it the best known of the class of ‘filled-centre’ supernova remnants (or ‘plerions’). It is powered by its central pulsar, and emits synchrotron emission with a relatively flat spectral index at radio wavelengths, with $\alpha \approx 0.3$ (with α here defined in the sense flux density $S \propto \nu^{-\alpha}$). The Crab Nebula has a high frequency spectral break in the mid-IR range (e.g. Marsden et al. 1984), which is at much higher frequency than that of other filled-centre remnants such as 3C58 (=G130.7+3.1; see Green & Scheuer 1992), which is consistent with the central pulsar in the Crab still being active.

At radio wavelengths there have been several claims of variations in spectral index across the Nebula, but apart from variations close to the pulsar, the other claimed differences (between the filaments and the diffuse inter-filament regions; a systematic steepening of the spectrum towards the edge of the remnant) were not confirmed by Bietenholz et al. (1997). Any variations are difficult to detect over a narrow range of wavelengths, and are more easily detectable if a good sub-mm image of the Crab Nebula is available for comparison with longer wavelength radio observations. Here I present new sub-mm observations of the Crab Nebula.

2. Observations and Data Reduction

The Crab Nebula was observed with the *Submillimetre Common-User Bolometer Array* (SCUBA) (Holland et al. 1999) using the ‘850 μm ’ filter on the James Clerk Maxwell Telescope (JCMT) on 1999 August 19. The 850 μm SCUBA filter is actually centred at 863 μm (i.e. 347 GHz). At this wavelength SCUBA

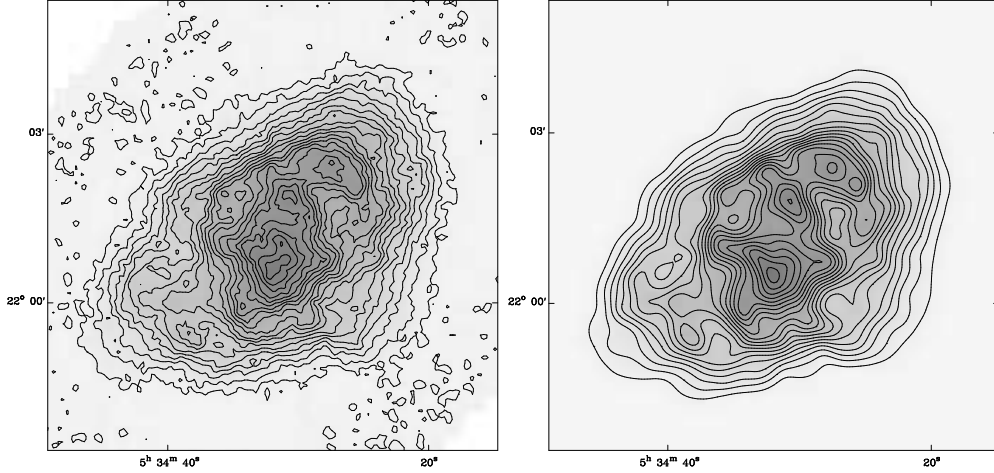


Figure 1. The Crab Nebula at: (left) 850 μm (347 GHz) from these JCMT observations (contours every 0.07 Jy beam $^{-1}$); (right) 20 cm (1515 MHz) from VLA observations (contour every 0.4 Jy beam $^{-1}$).

has 37 bolometers, each with an ideal resolution of 13 arcsec, covering a field-of-view of ~ 2 arcmin. Since the Crab Nebula is significantly larger than the SCUBA field-of-view, the observations were made in the **scan-map** mode, where the array scans across the source with the telescope continuously ‘chopping’ in a particular direction. A variety of chop-throws and scanning directions were observed, in order to sample structure well in all directions, and on scales missed by any particular chop throw. In total six chop throws were used (30, 44 and 68 arcsec in both RA and DEC), each for three different scanning directions (at PAs of 15 $^\circ$.5, 75 $^\circ$.5 and 135 $^\circ$.5). A region 9×7 arcmin 2 , at a PA of 45 $^\circ$, was observed in order to ensure a clear emission-free region around the Crab Nebula was covered. The observations were made in two sessions, over about 4.5 hours, at elevations between $\sim 60^\circ$ and $\sim 80^\circ$. Each session was preceded by observations of the standard source CRL 618, and was preceded and followed by a sky-dip calibration. The observing conditions varied little, as indicated by both the sky-dip observations, and the Caltech Submillimeter Observatory ‘tau-meter’ readings at 225 GHz.

The data were first reduced using a series of standard procedures from the *SCUBA User Reduction Facility* (SURF) package (see Jenness & Lightfoot 2000). This processing included corrections for the extinction at 850 μm , as measured by sky-dip observations (the observed optical depths varied between 0.19 and 0.21); removal of spikes in the data, both manually and automatically; removal of poorly-performing bolometers; removal of linear baselines; and removal of sky contributions. Finally the data were restored to an image using a MEM algorithm (Pierce-Price 2001). The flux density scale was set by the observations of the calibrator source CRL 618 (with an assumed flux density of 4.7 Jy), and the integrated flux density of the Crab Nebula on this scale was found to be 195 Jy, in good agreement with what is expected. From the CRL 618 observations the beam was fitted with a Gaussian of HPBW of 16 arcsec.

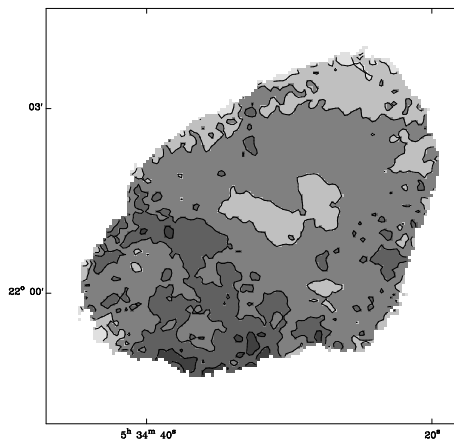


Figure 2. The spectral index, α , of the Crab Nebula between 20 cm and 850 μm . Contours, and discrete changes in the shading, are at 0.28, 0.31, 0.34 and 0.37 (higher spectral index is darker).

3. Results and Discussion

Figure 1 shows the emission from the Crab Nebula at 850 μm from these observations, smoothed slightly to a resolution of 17 arcsec, and a VLA image at 20 cm at the same resolution. The VLA image is from observations made in 1987, and it has been expanded by 1% to correct, simplistically, for the expansion of the Crab Nebula. The contours have been chosen to be at similar relative levels at each wavelength. Note that the 20-cm image is of higher quality, both in terms of its lower noise and the accuracy of the local baselevels. The noise on the 850 μm image, in small regions away from the Crab Nebula, is $\sim 0.015 \text{ Jy beam}^{-1}$, with variations in the local baselevel away from the Crab Nebula, up to $\sim 0.05 \text{ Jy beam}^{-1}$. The close similarity between these images – which are at wavelengths that differ by a factor of *over two hundred* – show that there is no strong spectral index variation across the remnant.

Figure 2 shows a spectral index image of the Crab Nebula between 20 cm and 850 μm . The spectral index, α , has been calculated where the 850- μm emission exceeds 0.2 Jy beam^{-1} . The uncertainty in the derived spectral indices are dominated by the uncertainty in the baselevel of the 850- μm image, and are ~ 0.05 at worst, near the edge of the data shown in Fig.2. Over most of the Crab Nebula the spectral index between 1.5 and 345 GHz is between 0.31 and 0.34, with no obvious indication of spectral steepening towards the edge of the remnant. The main deviations from these typical values for the spectral index occur: i) in the NW and SE of the remnant, which show steeper and flatter spectra respectively; and ii) near the centre of the remnant, where there are regions with slightly flatter spectra than their surroundings (which is similar to the results of Bandiera in these proceedings, who made spectral index comparison of 230-GHz observations with those at lower frequencies). The first of these differences corresponds to a large scale spectral index gradient across the Crab Nebula, which could be due to systematic uncertainties in the 850- μm image. The uncertainties in the 850- μm image include the varying background

level, the accuracy of the absolute position of the image, and the fact that SCUBA observations do not well sample the larger scales of the emission from the Crab Nebula. It is not thought possible that systematic uncertainties in the local baselevel and absolute position of the 850- μ m image could produce the NW to SE gradient. (Note, however, that the apparently steeper spectrum emission at the extreme southern edge of the Crab Nebula shown in Fig.2 is likely to be due to the low baselevel in this vicinity.) Given the limited sensitivity to large scale structure in SCUBA image, the apparent small spectral index gradient across the remnant may well be due to the different effective sampling of large-scale structures in the 850- μ m and 20-cm images. However, if it is real, the variation may be due to differences in the spectra of the particles injected into the NW and SE parts of the Crab Nebula from its central pulsar, or may reflect different environments (e.g. magnetic fields) in the NW part of the Crab Nebula compared with the SE. I note that in X-rays – for example from recent Chandra observations (Weisskopf et al. 2000) – there is also a NW to SE asymmetry (with the NW being brighter), indicating differences in the energetic relativistic particles and magnetic fields responsible for the X-ray emission. The regions of flatter spectrum emission near the centre of the remnant may be indicative of real variations in the spectral index between 1.5 and 347 GHz. However, given the 10 year difference between the observations 850- μ m and 20-cm observations, it may instead reflect temporal variations, and further comparisons of the 850- μ m image with other, cm-wavelength radio images will be made to investigate this further.

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